Studies for Students

THE CONSTITUENTS OF METEORITES. II

Glass.—This is an abundant constituent of the stone meteorites, few if any being entirely without it. It is variously distributed, occurring now as vein matter, now scattered through the substance of chondri, now enclosed in the substance of a single mineral, and now enclosing various minerals.

In the Parnallee, Mezo-Madaras, Chassigny, Farmington and a few other meteorites it has been described as forming a network in which the other minerals are imbedded. Its ocurrence in this manner is rare, however, it playing usually a merely accessory part. It chiefly abounds as inclusions and intergrowths in chrysolite, taking in this association a great variety of forms. Other minerals too, frequently have inclusions of glass. It may occur in fragments of considerable size or the particles may be of a dustlike minuteness.

Its abundance in chondri has already been mentioned. By all these occurrences a rapid crystallization or cooling of the meteorite substance is strongly indicated. Like the glass of terrestrial lavas it seems to be the result of cooling so rapid as to prevent differentiation and orderly crystallization of the magma. The especial abundance of glass in meteoritic chrysolite, the least fusible and therefore the earliest cooling ingredient further favors this conclusion.

The prevailing color of the glass of meteorites is brown. Much is however colorless and some occurs so dark as to be opaque. Grayish and greenish tones occur but are rare.

Chromite.—Nearly all stone meteorites give on analysis a small percentage of chromium which is usually considered as being present in the form of chromite, FeO,Cr_2O_3. The mineral is not so abundant in the iron and iron-stone meteorites

but has been detected in several and in the Coahuila irons occurs in nodules of considerable size ($17^{mm} \times 12^{mm}$).

It is identical with terrestrial chromite in composition and properties. Not being acted upon by acids, it may be readily distinguished from daubréelite. It is generally non-magnetic, but sometimes feebly magnetic. Where crystals occur they are commonly octahedrons, sometimes modified by other forms.

Amorphous carbon.—Meteorites of the group known as carbonaceous meteorites, as well as some others, are permeated by a dull-black pulverulent coloring matter which is usually left as a residue on treatment of the meteorite with acid. This residue sometimes amounts to from 2–4.5 per cent. of the mass.

A residue similar in character though smaller in amount is likewise found after dissolving many of the iron meteorites. These residues on being heated in air glow, usually become lighter in color and give off carbon dioxide. They must therefore be considered practically pure carbon.

Berzelius and Wöhler believed this carbon to have originated so far as the carbonaceous meteorites are concerned, from the decomposition of the hydrocarbons of the latter. In this respect they regarded it analogous to terrestrial humus, though of very different origin. Smith considered it similar in origin to the graphite of iron meteorites and Weinschenk believes it similar to one of the forms of carbon produced in the making of cast iron. No indications that it had an organic origin have ever been discovered.

Diamond.—The existence of diamonds has been definitely proven in only two meteorites, those of Cañon Diablo and Nowo-Urei. Diamonds have, however, also been reported from the irons of Magura and Smithville and the stone of Carcote. The diamonds of the Cañon Diablo meteorites have been most studied. Here they are found as minute particles or dust left as a residue after dissolving the meteorite in acid. The particles rarely exceed $\frac{1}{2}^{mm}$ in diameter. They are usually brown to black in color but sometimes are colorless and transparent. They accompany graphite, amorphous carbon and often troilite

and schreibersite. They have a tendency to gather in little clefts or hollows and are not regularly distributed. Their character as diamond is proven chiefly by their hardness, but analyses and a study of their behavior in polarized light give confirmatory results. Huntington found some also which showed crystal forms of diamonds. The occurrence of diamonds in meteorites suggests interesting analogies with their terrestrial occurrence. Knop and Daubrée call attention to the fact that the peridotic rocks in which terrestrial diamonds occur are the rocks most nearly allied in composition to meteorites. In the iron meteorites, as Moissan has proven satisfactorily by experiment, diamond is to be considered a form in which, under certain conditions of heat and pressure, carbon separates. Moissan obtained diamonds by heating to a high temperature iron saturated with carbon and allowing it to cool under pressure. The carbon was then found to exist in three forms, graphite, foliated carbon, and a diamond powder which latter corresponded to that obtained from the Cañon Diablo meteorites.

A form of carbon resembling graphite but differing in having a hardness of 2.5 and being isometric in crystallization, has been noted in the Magura, Cosby's Creek, Youndegin, Toluca and a few other iron meteorites. It was first discovered by Fletcher, who considered it a distinct species and gave it the name cliftonite. Other authorities, however, regard cliftonite as a pseudomorph after diamond, since its crystals closely resemble those of diamond in form.

Daubréelite.—This mineral is an iron-chromium sulphide peculiar to meteorites. Its composition is $Fe\,S, Cr_2\,S_3$. It is found in nearly all the cubic iron meteorites and has also been identified in the irons of Toluca, Nelson county, Cranbourne, Cañon Diablo and others. It has never been found in stone meteorites. It usually accompanies troilite, either bordering nodules or crossing them in veins. Sometimes, however, it occurs as thin plates or grains. It is black in color, has a black streak, is of metallic luster, brittle and not magnetic. It is infusible before the blowpipe and becomes magnetic in the reducing flame. It is not

attacked by hot or cold hydrochloric acid, but is completely dissolved by nitric acid without the separation of free sulphur. This solubility distinguishes it from chromite. Its system of crystallization is not known though it exhibits rectangular and triangular partings which indicate one of the systems of high symmetry. Meunier obtained the mineral artificially by treating an alloy of iron and chromium at a red heat with hydrogen sulphide.

Tridymite.—This mineral has been positively identified in only one meteorite (Steinbach), but it probably also occurs in the Vaca Muerta and Crab Orchard Mountains meteorites. These are all ironstone meteorites. In the Steinbach meteorite it forms from 8.5 to 33 per cent. of the non-metallic constituents and occurs intergrown with bronzite.

Maskelyne, who first described the mineral, considered it on account of its optically biaxial character a new orthorhombic form of silica and gave it the name of asmanite. Since tridymite is now known, however, to exhibit biaxial characters and the minerals agree in most other respects, they are generally considered identical.

Tridymite occurs in meteorites in the form of rounded grains or plates, some of which reach a length of 3^{mm}. They are colorless to white to rusty brown in color.

Well developed crystals are rare but from facets on rounded grains a total of twelve forms has been determined.

Analyses show a composition of practically pure silica, with iron oxide and magnesia present as impurities.

Lawrencite.—This is a solid ferrous chloride which has been described from the iron meteorites of Tazewell, Smith Mountain, and Laurens county. Formula $Fe\,Cl_2$. Color green to brown. While described in the solid form from only the few meteorites mentioned, the presence of lawrencite in many other iron meteorites is generally believed to be indicated by the greenish drops which exude on their surfaces. These drops are ferric chloride or mixtures of ferric and nickel chloride, while occasionally pure nickel chloride occurs.

The meteorites from which ferric chloride exudes disintegrate with especial rapidity. Such meteorites are often known as "sweating" meteorites. The "sweating" is rarely noted in ironstone or stone meteorites, but the small percentage of chlorine found in the analysis of many of these meteorites is usually referred to lawrencite. Some authorities hold that the substance is not an original constituent of any meteorite, but is wholly of terrestrial origin. This is not the general opinion however.

Ferrous chloride has been noted among the sublimation products at Vesuvius and is reported as having been found in the terrestrial nickel-iron of Ovifak.

Magnetite.— Several stone or ironstone meteorites have been found to contain black, magnetic grains which dissolve in hydrochloric acid without effervescence to form a yellow solution.

In the meteorites of Shergotty and Doña Inez these are sufficiently abundant to form an essential constituent. They constitute 4.57 per cent. of the Shergotty meteorite. Similar grains occur as inclusions in maskelynite, pyroxene, and chrysolite in the above and other meteorites. They are regarded as magnetite.

No well marked crystals of meteoritic magnetite have as yet been described.

Magnetite has been reported as a constituent of several iron meteorites though only one analysis has been made, that of Meunier of magnetite from the crust of one of the Toluca irons. The composition of this agreed with that of terrestrial magnetite. Several other iron meteorites show magnetite in their crust. Here, however, the magnetite may have originated from the oxidation of the iron of the mass since its arrival upon the earth.

Magnetic spherules have been dredged up from ocean depths, which Murray and Renard regard as particles of meteoric iron oxidized to magnetite since their arrival upon the earth.

Oldhamite.—This is a simple calcium sulphide with the formula $Ca\ S_2$. Grains of it were found by Maskelyne embedded in the enstatite or augite of the Bustee meteorite. It is light

brown in color and transparent when pure. Hardness 4, specific gravity 2.58. It is isotropic and has equal cleavage in three directions, hence is doubtless isometric. In the Bustee meteorite it occurs in rounded grains, coated with gypsum through alteration.

Certain yellow grains found in the Bishopville meteorite were also considered by Maskelyne to be this mineral. Aside from these two occurrences it has not been positively identified in any other meteorite.

Calcium sulphide resembling oldhamite was obtained by Maskelyne by heating caustic lime in a glass tube, first with hydrogen, then with hydrogen sulphide. Vogt has noted a similar compound formed in furnace slags.

It has not been found as a terrestrial mineral.

On dissolving the oldhamite of the Bustee meteorite, Maskelyne found a residue constituting about 0.3 per cent. of the weight of the former, consisting of yellow octahedrons of microscopic size. These were found to be unaffected by acids or oxygen, while qualitative tests indicated sulphur, calcium, and titanium or zirconium. Maskelyne regarded the mineral therefore an oxysulphide of calcium and titanium and gave it the name osbornite. No other occurrence of the mineral is known.

Hydrocarbons.—The hydrocarbons found in meteorites may be divided, following Cohen,[1] into three classes: (*a*) compounds of carbon and hydrogen; (*b*) compounds of carbon, hydrogen and sulphur; and (*c*) compounds of carbon, hydrogen and oxygen. They especially characterize meteorites of the class known as carbonaceous, which includes seven or eight distinct falls of meteorites of black color, low specific gravity and containing a sensible amount of carbon. They have been obtained from some other meteorites however, such as those of Collescipoli and Goalpara. The hydrocarbons of the first class are obtained by treating these meteorites with alcohol or ether. They are resinous or wax-like bodies which completely volatilize on the application of heat. When heated in a closed tube the resinous substances first fuse,

[1] Meteoritenkunde. Heft. I, p. 159.

then are decomposed to form amorphous carbon and an oil hav-a bituminous or fatty odor. Such substances were considered by Wöhler similar to the mineral wax ozocerite and by Shepard they were designated meteoritic petroleum. Friedheim states that a substance extracted by him from the meteorite of Nagaya by means of ether had a bituminous odor, volatilized at 200° and resembled a product of distillation of brown coal. A similar substance extracted by Roscoe from the meteorite of Alais was found to have a composition corresponding nearly to the formula $C\,H_{2n}$.

Hydrocarbons of the second class were obtained by Smith by treating the graphite of iron meteorites and some carbonaceous meteorites with ether. These compounds were fusible and volatile. He regarded them as having the general composition $C_4H_{12}S_5$. He obtained similar products by treating cast iron with ether or petroleum as did also Berthelot by the action of ether on sulphur or iron sulphide in the presence of oxygen.

Hydrocarbons of the third class have been obtained from the meteorites of Orgueil and Hessle. The Orgueil extract resembles peat, humus or lignite in its composition and properties. That from Hessle has approximately the composition $n\,C_9H_8O_2$.

The above mentioned facts make it clear that a number of meteorites contain products of an easily destructible, volatile, and combustible character which resemble terrestrial bitumens, petroleum or oxygenated hydrocarbons. The quantity of these products is relatively small, being less than 1 per cent. in the majority of meteorites in which they occur. Yet that they occur at all is significant. While some have urged that these products might have arisen from the union of their elements in the terrestrial atmosphere there seems little reason for doubting their pre-terrestrial origin. There is no evidence that life had anything to do with their origin. We must conclude then that they were formed in an inorganic way by a union of their elements. The conclusion at once suggests the possibility that

terrestrial hydrocarbons need not always be referred to an organic origin, but may have been formed in a purely inorganic way.

The occurrence of hydrocarbons in meteorites further shows that such meteorites could not have been subjected to any high degree of heat subsequent at least to the formation of these compounds, and that the heating of meteorites during their fall to the earth has in many cases been only superficial.

The trails of light, sometimes enduring several minutes, observed following in the wake of some meteors may perhaps indicate the presence of carbonaceous matter in those bodies. The stone shower which took place at Hessle was accompanied by luminous effects and with the stones fell a brownish-black powder which contained 71 per cent. carbonaceous matter. Other carbonaceous meteorites have fallen, however, without exhibiting any marked luminous phenomena.

Other compounds.— Besides the above well-determined compounds a number of others have been reported at different times which are (1) present in insignificant amount or (2) their occurrence has not been confirmed, or (3) they may be of terrestrial origin. Among these a few may be mentioned: *Quartz.* This mineral, as is well known, is remarkable for its absence from meteorites. Yet it doubtless does occur in minute grains in a number of iron meteorites, since on dissolving them a residue is left, the grains of which possess the properties of quartz. Its occurrence in any stone or ironstone meteorite has never yet been established. *Pyrite.* This mineral has been reported a number of times, but sufficient proof to establish its identity has not been given. Von Siemaschko reported from the meteorite of Ochansk a brass-yellow pentagonal dodecahedron of which, however, he gave no measurements. Daubrée found in the meteorite of Senhadja, bronze-yellow grains insoluble in hydrochloric acid, soluble in aquaregia and altering easily to iron sulphate. While these and other observations suggest pyrite they are not conclusive. *Salts soluble in water.* Several of the carbonaceous meteorites as well as one or two others give

on evaporation of the water extract a residue of soluble salts reaching in quantity in one case as high as 10 per cent. of the mass. These salts include nickel, calcium, magnesium, potassium, sodium and ammonium sulphates and chlorides.

Since the meteorites in which they occur are very porous in character and show other signs of alteration these compounds are usually considered to be formed by terrestrial modification of the meteorite and not to exist as original constituents. Daubrée, however, gives good reasons for regarding the sodium chloride which he found in the Lancé meteorite an original constituent. These reasons are that the meteorite had lain only three days in a clayey bed before it was picked up and no salt is known to have come near it. *Breunnerite.* This mineral was found in the meteorite of Orgueil occurring in the form of little transparent crystals. The identity of the mineral was established both by qualitative tests and by goniometric measurements. It has been suggested that it was of secondary origin. As it was found well within the interior of some masses, this, however, hardly seems likely. This is the only carbonate known from meteorites.

A number of other minerals have been reported from meteorites without sufficient grounds, according to the writer's view, to support the conclusion. Cohen considers them doubtful while Meunier accepts most of them. These are: *Apatite, iolite, wollastonite, titanite, garnet, vesuvianite, mica, aragonite, leucite, cassiterite, hornblende, anthophyllite and orthoclase.*

Mineral aggregates.—The different aggregates which the compounds above described form in different meteorites are too various to be recorded here in detail. For an account of these, reference should be made to the elaborate classifications of Meunier,[1] Brezina[2] or Wülfing.[3]

A few general observations may be made here, however, following the lines of the classification given by Wülfing. The

[1] Revision des Pierres Météoriques. Paris, 1897.

[2] Annalen des k. k. Naturhistorischen Hofmuseums. Bd. X, Heft 3 u. 4. Vienna, 1896.

[3] Die Meteoriten in Sammlungen. Tübingen, 1897, pp. 447–460.

iron-meteorites, as already indicated, are made up chiefly of nickel-iron, with schreibersite, troilite, daubréelite and a few other minerals occurring as accessories.

Of the ironstone meteorites the largest quantity are of the so-called pallasites, formed chiefly of chrysolite and nickel iron. Nine falls of this group are known, having a weight of 1742 kilograms. In the group known as siderophyrs, represented by one fall (82 kilos), of meteoritic matter, bronzite and tridymite are associated with the nickel-iron. In the group of mesosiderites (grahamites) represented by ten falls (483 kilos), of meteoritic matter, the nickel-iron is accompanied by chrysolite, bronzite, plagioclase, and augite. In the group lodranite, composed of one fall with a weight of 1 kilo, chrysolite and bronzite are associated with nickel-iron.

Passing to the stone meteorites the following groups and weights may be noted:

A. Stones rich in calcium and magnesium and containing little or no nickel-iron.

1. Angrite. Chiefly augite. One fall, weight 0.4^{kg}.
2. Eukrite. Augite and anorthite. Four falls, weight 91^{kg}.
3. Shergottite. Augite and maskelynite. One fall, weight 5^{kg}.
4. Howardite. Augite, anorthite, bronzite, and chrysolite. Ten falls, weight 5^{kg}.

B. Stones rich in magnesia and containing little or no nickel-iron.

1. Bustite. Diopside and bronzite. Two falls, weight 1.7^{kg}.
2. Chassignite. Chiefly chrysolite. One fall, weight 0.9^{kg}.
3. Chladnite. Chiefly orthorhombic pyroxene. Four falls, weight 9^{kg}.
4. Amphoterite. Chiefly chrysolite and bronzite. Three falls, weight 40^{kg}.

C. Stones rich in magnesia and consisting essentially of chrysolite, bronzite, nickel-iron, and iron sulphide. Here belong the great majority of stone meteorites.

A comparison of the constituents as above described with those of the crust of the earth brings to view some interesting similarities and contrasts. Under *similarities* may be noted the fact that the elements of meteorites are the same as those of the earth and that they unite according to the same chemical and physical laws. No new element has been discovered in meteorites and the chemical compounds of meteorites similar to those of the earth agree even to the details of their crystal form.

Under *contrasts* it may be noted that two agents which have affected largely the composition of the crust of the earth have been lacking either wholly or in part in the formation of meteorites. These agents are water and oxygen. The lack of water is proved by the fresh and unaltered character of the minerals found in meteorites and the absence of all hydrous minerals. Thus the chrysolite of meteorites is never found serpentinized nor are the pyroxenes changed to chlorite nor the feldspar to kaolin.

Further, zeolites, micas, epidote, tourmaline and all other minerals in the formation of which water and water vapor play a part are entirely lacking from meteorites.

Similarity, oxygen, at least in excess, is lacking from the constituents of meteorites. Such substances as nickel-iron, schreibersite, and lawrencite, which make up so large a part of the composition of meteorites would rapidly have been oxydized had they been exposed to the action of oxygen as it occurs upon the earth. The silicates of meteorites are however oxydized compounds which show that oxygen is present to some degree in space.

Again, as noted by Cohen,[1] the important rock-forming minerals of the crust of the earth are either lacking or play an insignificant part in the formation of meteorites. Such are quartz, orthoclase, the acid plagioclases, the micas, the amphiboles, leucite, and nepheline. Vice versa, the chief mineral constitutents of meteorites occur in but insignificant amount upon the earth. Such are nickel-iron, the orthorhombic pyroxenes and chrysolite, while such compounds as schreibersite, cohenite, lawrencite, oldhamite, daubréelite and troilite rarely or never occur terrestrially. Looked at quantitatively then it may be said that terrestrial rocks abound in free silica, lime, alumina, and alkalies, while meteorites abound in iron, nickel and magnesia. Whether these quantitative differences would be maintained if the constitution of the earth as a whole could be compared with that of meteorites, is, as hinted at the beginning, doubtful.

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[1] Op. cit., p. 323.